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NASA PROGRESS REPORT

SPATIAL CHARACTERIZATION OF ACID RAIN STRESS IN CANADIAN SHIELD LAKES

NASA Contract: NAS5-28779

Principal Investigator: Fred J. Tanis

Reporting Period: February 1, 1987 to August 1, 1987

1.0 OBJECTIVE

The acidification of lake waters from airborne pollutants is of continental proportions both in North America and Europe. A major concern of the acid rain problem is the cumulative ecosystem damage to lakes and forest. The number of lakes affected in northeastern United States and on the Canadian Shield is thought to be enormous. Our principal research objective is to examine how seasonal changes in lake transparency are related to annual acidic load. Further, the relationship between variations in lake acidification and ecophysical units is being examined. Finally the utility of Thematic Mapper (TM) based observations to measure seasonal changes in the optical transparency in acid lakes is being investigated.

Previous investigations have suggested that dissolved organic carbon (DOC), which originates from the dissolution of humic substances, controls transparency in most Canadian Shield Lakes. It has also been established that aluminum, which is abundant in the local rocks and soils, is easily mobilized by acidic components contained in spring runoff. The presence of any significant amount of aluminum induces a

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loss of DOC from the water column by coagulation, resulting in increased optical transparency (Effler et. al., 1985).

This process has not been observed in normal lakes associated with buffered geologies. In a normal lake, transparency would tend to decrease in time with seasonal phytoplankton productivity cycles. Thus seasonal changes in the optical transparency of lakes should potentially provide an indication of the stress due to acid deposition and loading.

The potential for this optical response is related to a number of local ecophysical factors with geology being, perhaps, the most important. Other important factors include sulfate deposition, vegetative cover, and terrain drainage/relief. The area of southern Ontario under study contains a wide variety of geologies from the most acid rain sensitive granite quartzite types to the least sensitive limestone dolomite sediments. Annual sulfate deposition ranges from 1.0 to 4.0 grams per square meter.

2.0 APPROACH

Water quality parameters are being measured along with insitu optical data in representative lakes in the Canadian Shield. This is being done to calibrate a Bio-Optical Model which defines the linkages between the acid rain induced chemical lake processes and the upwelling radiance sensed by the Thematic Mapper sensor on Landsat. A spring/summer scene pair with companion field measurements is being collected in selected study sites located in northern Ontario. These data will be used to investigate possible formulations of the multitemporal remote sensing causal relationships between pH and observed changes in water transparency.

It is hypothesized that a verifiable relationship exists between seasonal changes in water quality associated with the level of lake acidification and Thematic Mapper radiometry. The verified Bio-Optical

Model will be used to establish the limits for which such relationships are inherently valid, and together with the field data, the set of ecophysical units and water quality conditions where the Landsat approach is valid. Under these restrictions lakes within an ecophysical stratum will be assigned a value for the degree of acidification based upon the TM multitemporal relationship. These results will permit one to test the hypothesis that the severity of lake acidification is not uniform over large areas, but rather that variations exist which are strongly related to ecophysical units and proximity to probable sources of atmospheric inputs.

3.0 ACTIVITIES BY TASK

3.1 STRATIFICATION OF ECOPHYSICAL PARAMETERS (TASK 1)

The Canadian Shield area covered by three Landsat TM scenes has been stratified into ecophysical units based upon soil-bedrock sensitivity, vegetative cover, terrain-drainage, and acid deposition. The objective of this stratification is twofold. First, it is intended to reveal the location, status and co-occurrence of environmental attributes which influence lake acidification. Second, it provides a basis to characterize each lake within the study areas as an aid to the sampling design.

A total of 694 ecophysical units were mapped in three Landsat scenes. These units were clustered into ten distinct strata. The mean acidification sensitivity rating of these clusters ranged from 3.5 for low sensitive areas to 7.8 in the most highly sensitive strata. Field sampling included collections in nine of the ten strata.

3.2 SITE SELECTION (TASK 2)

Site selection was based upon the stratification and clustering analysis described above and each of the following considerations: (1)

availability of historical water quality and remote sensing data, (2) existing Canadian initiatives to collect site specific data, (3) accessibility, and (4) coverage of ecophysical lake types. Sites selected included (1) Algoma, (2) Sudbury, (3) Wawa, and (4) Dorset.

Field data collections were made on 5 May, 14 May, 13 June, and 29 June at 4,5,6,7, or 8 lakes located within the Sudbury site area. These data were collected coincident with the TM overpass on each of those dates. Two of these TM acquisitions 12 May and 13 June were of excellent quality and have been requested from NASA GSFC. Field data were collected repeatedly from several lakes using the Seatech transmissometer and MER-1000 submersible radiometer. Water samples were also collected and are currently being processed by the MOE. No PROBAR airborne radiometer data were collected during the spring period because the unit was not available.

3.3 LIAISON ACTIVITIES WITH THE CANADIANS (TASK 3)

A cooperative program with Canadian agencies and Universities interested in the remote sensing aspects of the acid rain problem have resulted in an informal joint program which includes four major Canadian participants. These are Professor Roger Pitblado of Laurentian University Sudbury, Ontario, Dr. John Fortescue of the Ontario Geological Survey (OGS), Dr. Vernon Singroy of the Ontario Centre for Remote Sensing (OCRS), and Professor Michael Dickman from Brock University, Saint Catherines, Ontario. The Canadians are funded through the Ministry of Environment (MOE) and the Ontario Geological Survey.

3.4 DEFINITION OF MULTITEMPORAL RADIOMETRIC RELATIONSHIPS TO ACIDIFICATION (TASK

In this task a TM radiative transfer model will be calibrated to predict possible multitemporal changes in signal level which result from field measured changes in optical and chemical properties. Work has

proceeded on this model to include specific calibration for the Landsat TM sensor. The model treats atmospheric optics, water optics, and the wind ruffled air-water interface. A solar ephemeris model has also been implemented to provide a capability to simulate the entire sun-sensor geometry. For many of the lakes involved in this study absorbing effects of DOC dominates the scattering effects of suspended minerals and organic particles. Under theses conditions subsurface reflectance can be estimated as the ratio of backscattered radiation to the total lost by both backscattering and absorption.

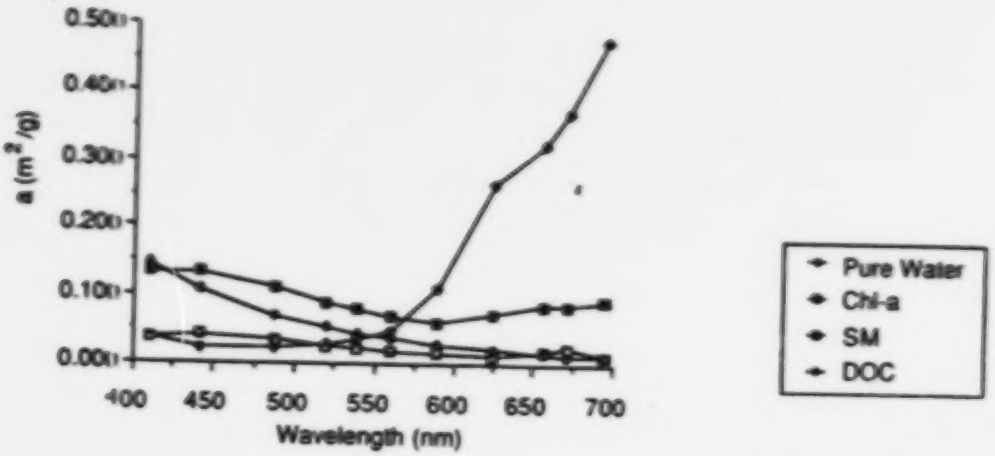
$$R(\lambda) = C(\lambda) \cdot \frac{Bb(\lambda)}{a(\lambda)+Bb(\lambda)}$$

where:

$R(\lambda)$ = Subsurface Reflectance
$C(\lambda)$ = Constant (Typical Value = 0.33)
$Bb(\lambda)$ = Total Backscattering Coefficient
$a(\lambda)$ = Total Absorption Coefficient

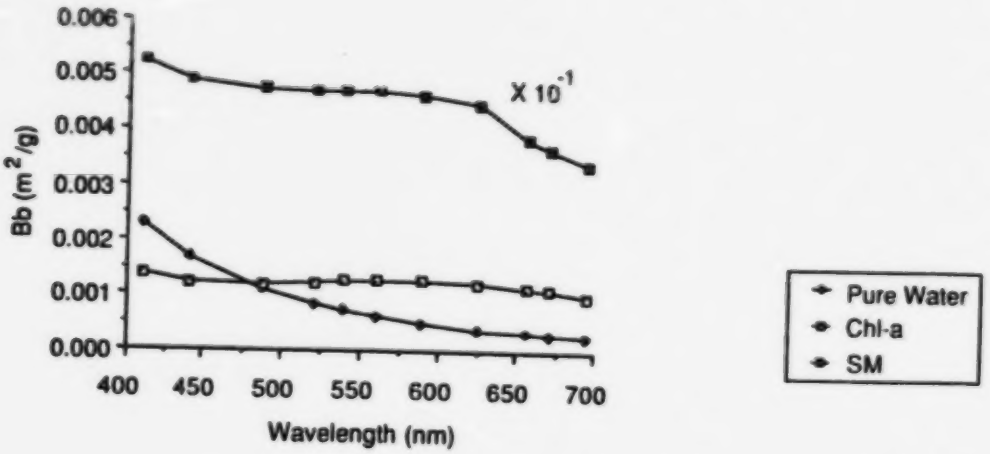
The specific values of a and Bb will depend on the concentrations of silt (mineral particles), chlorophyll-a pigments (CHL-a), and DOC. The absorption and scattering cross sections used in the present study were those derived by Bukata [1985] in his detailed optical analysis of Lake Ontario waters. These cross sections are shown in Figures 1 and 2.

The specific concentrations of each component were used together with these cross sections to estimate the absorption and backscattering coefficient. These values regressed with the MER-1000 estimated subsurface reflectance at each wavelength producing an estimate of constant coefficient (C) which is listed in Table 1. The resulting set of reflectance equations can be used to examine the spectral reflectance



Bukata et. al.
1985

FIGURE 1. ABSORPTION CROSS SECTIONS FOR CHLOROPHYLL-a, DOC, SUSPENDED MINERALS, AND THE ABSORPTION COEFFICIENT OF PURE WATER



Bukata et. al.
1985

FIGURE 2. BACKSCATTER CROSS SECTIONS FOR CHLOROPHYLL-a, SUSPENDED MINERALS, AND THE BACKSCATTER COEFFICIENT OF PURE WATER

TABLE 1. ESTIMATED COEFFICIENTS FOR THE PRELIMINARY REFLECTANCE MODEL

λ (nm)	C(λ)	Std. Error
410	0.731	0.1382
441	0.678	0.1193
488	0.525	0.0063
520	0.360	0.0318
540	0.319	0.0373
560	0.301	0.0520
589	0.374	0.0679
625	0.300	0.0753
656	0.345	0.0930
671	0.383	0.0936
694	0.519	0.1156

$$R(\lambda)=C(\lambda)\cdot\frac{Bb(\lambda)}{a(\lambda)+Bb(\lambda)}$$

Assumption:
[SM] = 0.1 mg/l

dependence on DOC and other constituents. The mineral particle concentrations were found to be extremely small, on the order of 0.1 mg/l. If we assume a chlorophyll-a concentration of 1.0 µg/l (a typical value) then the DOC reflectance varies between 1% and 6% in TM band one as depicted in Figure 3.

The ability to detect a seasonal change in the Landsat TM response will depend on the measured TM response to changes in reflectance, and on the sensitivity of reflectance to changes in DOC and chlorophyll-a pigment concentration. The sensitivity of reflectance to changes in DOC is given by the following derivative of the model equation.

$$\frac{dR(\lambda)}{d[DOC]} = - \frac{a_{DOC}(\lambda).(Bb_W(\lambda)+Bb_{SM}(\lambda).[SM]+Bb_{CHL}(\lambda).[CHL].C(\lambda)}{(a_{DOC}(\lambda).[DOC]+a_{CHL}(\lambda).[CHL]+a_{SM}(\lambda).[SM]+a_W(\lambda))^2}$$

Figure 3 shows the change in reflectance sensitivity for a given DOC concentration. The plotted sensitivity values are for the Sudbury site, calculated using the above equation and measured values of DOC and chlorophyll-a. The impact of DOC changes on reflectance and predicted TM band one counts can be calculated using the above equation and the expected TM band one count changes per percent subsurface reflectance change, which has been estimated previously to be 2.86 counts/%. If it is assumed that seasonal changes in DOC are on the order of 50%, the background levels then two to three count changes are projected in the TM response. These predictions are summarized as Table 2.

3.5 DATA PROCESSING (TASK 5)

Radiometric data processing and data reduction has involved three instruments (1) The Biospherical MER-1000 radiometer, (2) the PROBAR spectral radiometer, and (3) Landsat TM.

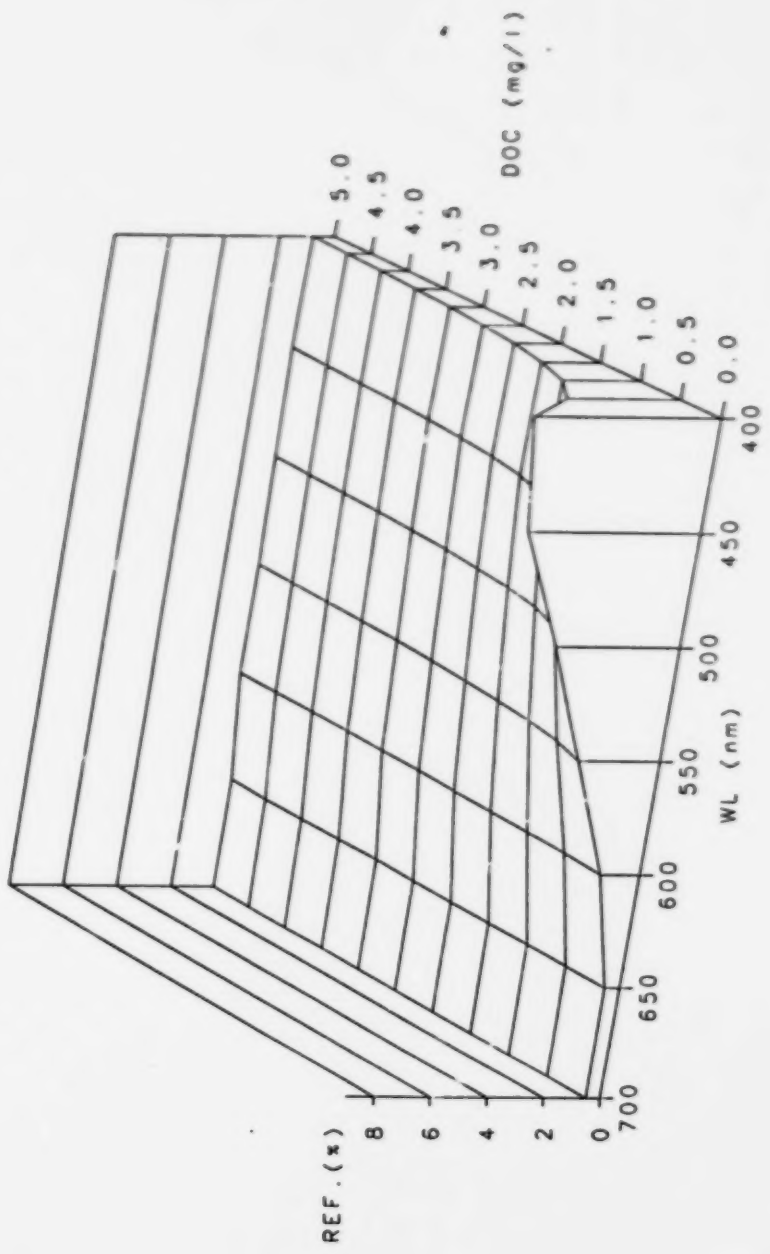


FIGURE 3. PRELIMINARY DOC REFLECTANCE MODEL

TABLE 2. PREDICTED CHANGES IN REFLECTANCE AND TM BAND 1 COUNTS

DOC SENSITIVITY	DOC (mg/l)	ΔDOC (mg/l)	ΔR(%)	ΔTM Counts
5.6	0.3	0.15	0.84	2.40
4.0	0.5	0.25	1.00	2.86
1.6	1.0	0.50	0.80	2.29
0.8	2.0	1.00	0.80	2.29
0.3	3.0	1.50	0.45	1.29

The MER upwelling and downwelling spectral irradiance data were collected in the field at variable sampling depths below the lake water surface as indicated by a sensitive pressure sensor. These data were first used to linearly interpolate the irradiance data to common depths before computing values of subsurface reflectance. The slope of the depth log irradiance regression equation defines the average irradiance attenuation coefficient (K). Since the irradiance attenuation coefficient changes very little within the mixed layer, and more rapidly within the transition zone, only mixed layer measurements were used to make the K-value determination.

The airborne PROBAR measurements were made by helicopter. The rotating blade interfered with the downwelling irradiance meter and also possibly with the upwelling radiance measurements as well. The raw data from several dates showed a significant change in downwelling irradiance between measurements taken on the ground using a standardized white reflectance card. This discrepancy is attributed to changes in helicopter blade tilt. The blade tilt affects the amount of shadow interference to the irradiance meter. The impact of this blade effect was dependent on time of day and date illumination conditions. These conditions necessitated a series of five corrections be made to these data in order to make them compatible to the MER reflectance data. These corrections were for (1) standardized white card reflectance, (2) for airborne conditions, (3) for time of day, (4) for day-to-day variations in sky illumination, and (5) to subsurface reflectance.

The TM DN values were extracted for each lake as the mean and standard deviation value for a 3 by 3 pixel data set. The standard deviations of these mean DN values were generally less than 0.5. Spatially varying haze was found to be the chief cause of elevated DN values. The noisy impact of haze was reduced by normalizing data for haze using TM band four. The scheme used is given by the following equation.

TM 1 (corrected) =
TM 1 (raw) - TM 1 (dark lake) - κ(TM 4 (raw) - TM 4 (dark lake))
where κ is Relative TM 1 - TM 4 Haze Coefficient

This procedure reduced the impact of haze as indicated by the improved correlation between TM band one DN values and DOC (i.e. from 0.62 to 0.83).

3.6 DETERMINE RELATIONSHIPS WITH FIELD DATA (TASK 6)

In this task the relationships that exist between lake water quality, optical measurements, and TM radiometry with lake acidification are being determined. The relationship between each instrument and the WQ parameters has been examined. First, we have found the MER reflectance data to reasonably fit a simple reflectance model. Second, the PROBAR derived reflectance data were found to be highly correlated to the MER reflectance as shown by the examples in Figure 4. The PROBAR reflectance data provides a means to check the validity of a reflectance model across a much larger set of lakes than are available with MER results. Figure 5 shows PROBAR correlations with DOC and pH at multiple wavelengths. These plots show, as expected, that greatest reflectance sensitivity is at the shorter wavelengths and suggest that TM bands one and possibly two will be sensitive to reflectance changes induced by changes in DOC.

The haze normalized TM data for August 1986 do show sensitivity to lake DOC concentration as indicated by the data plotted in Figure 6. These results confirm the model predicted sensitivity of TM band one DN counts to changes in DOC. The model predicted a DOC reflectance range of about 5% which corresponds to a 14.3 DN count spread in the TM band one data. TM data from the Sudbury site are consistent with the predicted spread in DN counts. The Algoma data appear to lack sensitivity to changes in DOC which is likely due to the fact that most lakes in the Algoma region have high values of DOC and chlorophyll-a.

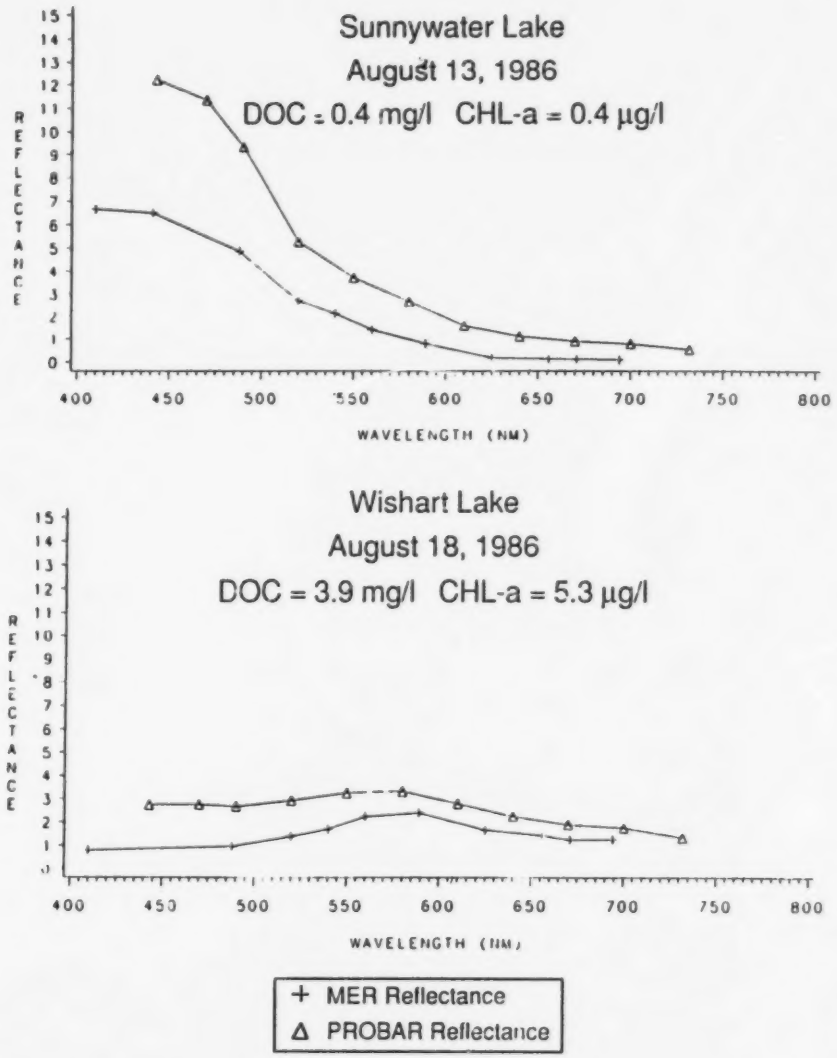


FIGURE 4. COMPARISON OF MER AND PROBAR REFLECTANCES

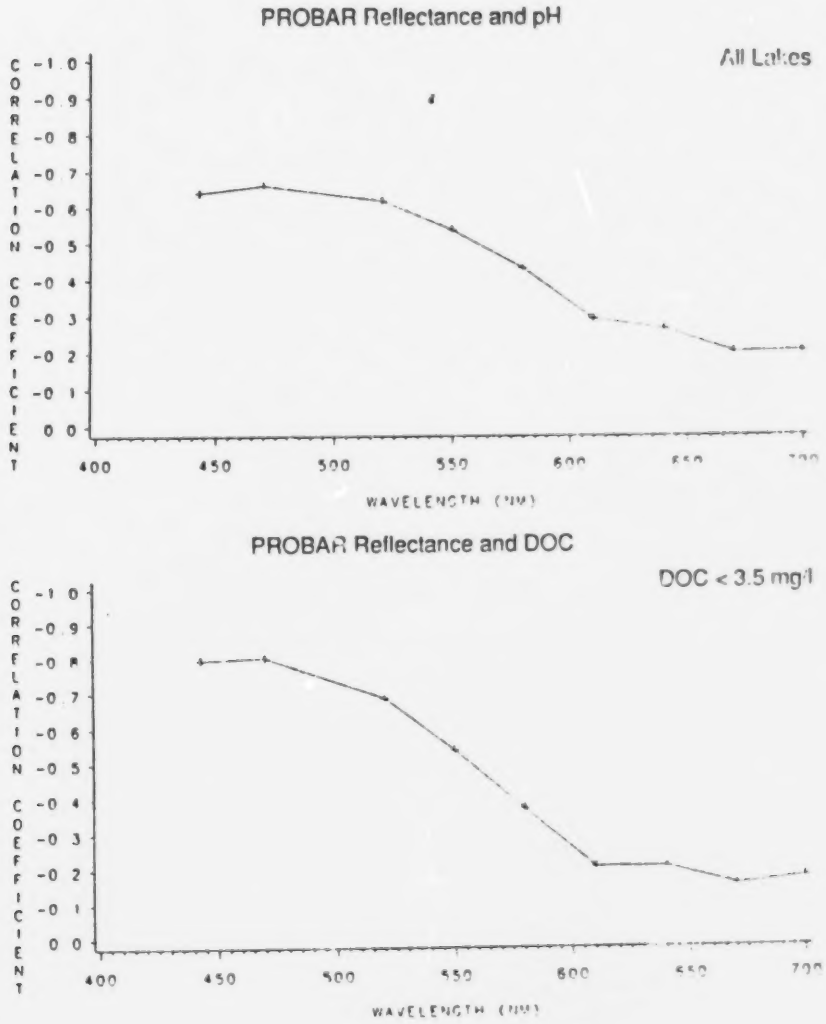


FIGURE 5. PROBAR CORRELATION ANALYSES

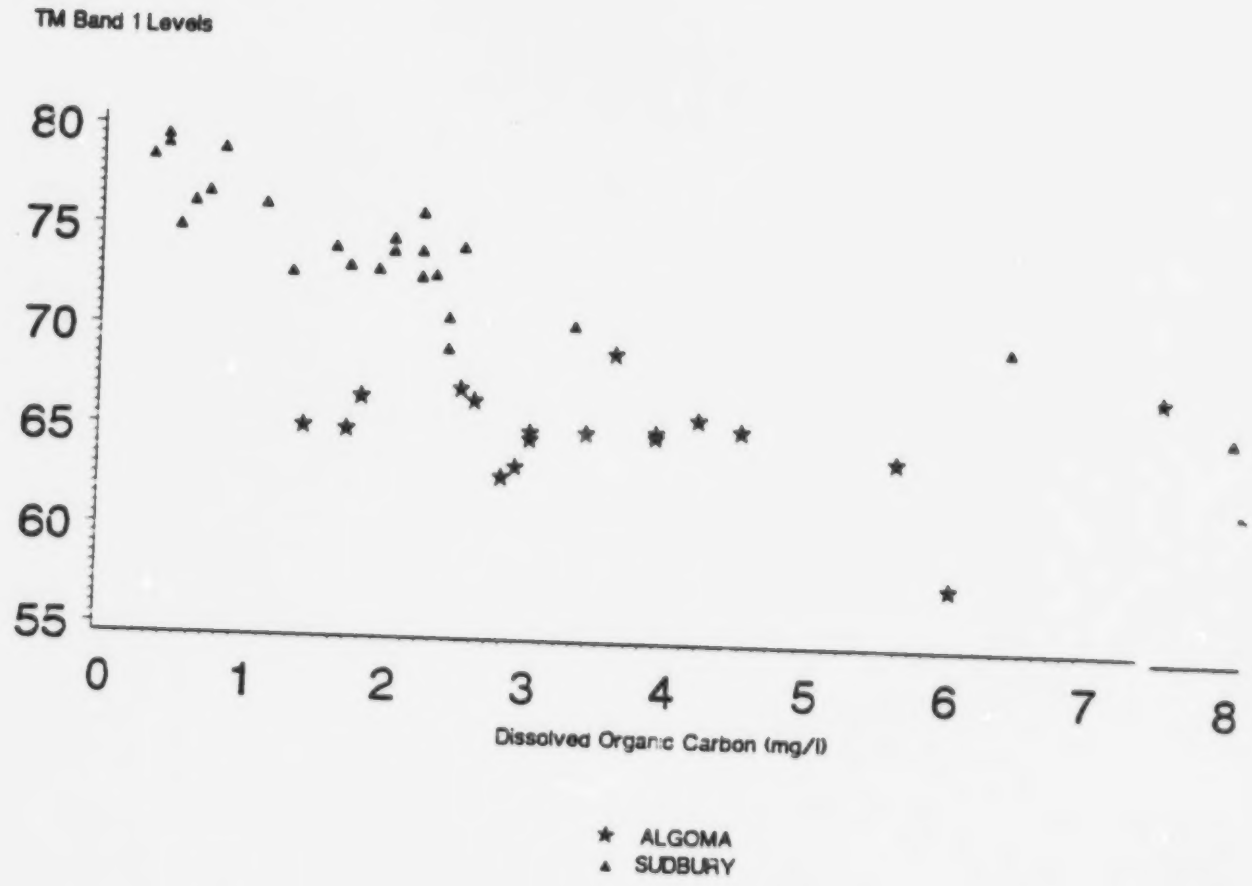


FIGURE 6. TM BAND 1 VERSUS DISSOLVED ORGANIC CARBON FOR ALGOMA AND SUDBURY SITES, AUGUST 1986 DATA

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The TM band one seasonal change patterns are similar to those indicated for the August 1986 data. The August low DOC lakes were found to have larger TM DN values than with the May date or a positive change for the Sudbury August-May change pair and the magnitude of change was found to be related to DOC(as shown in Figure 7). By contrast the changes for Algoma were smaller, mostly negative, and unrelated to DOC. The size of the TM band one count changes for Sudbury are substantially larger than predicted. These count differences suggest a two to three percent change in subsurface reflectance, needed a greater DOC change sensitivity than predicted in Table 2.

3.7 SPATIAL ASPECTS OF ACIDIFICATION (TASK 7)

An analysis will be performed to interpret the spatial aspects of lake acidification. In this task three types of relationships have been investigated based upon the August - May seasonal scene pairing. The May data used thus far have been the historical data from 1984 and 1985 described earlier in this report. In the first type of analysis ANOVA was used to examine the mean TM band one count by ecophysical strata. Are the TM band one DN values significantly different between strata? For the August 86 composite Algoma and Sudbury data sets, two groupings were identified. Group A with lakes in strata 5,7, and 9 had mean DN values (73.5 to 75.9) which were significantly different (at 5%) than DN values (64.8 to 67.5) from lakes in strata 2,4,and 8 (i.e. group B). The mean ecophysical sensitivity of group A strata was 7.44 while group B was 5.85. The largest DN values measured were from strata 7 with a mean sensitivity index of 7.07 and the smallest from strata 4 with a sensitivity index of 6.07. The primary difference in these two ecophysical strata is the soil type and depth over the underlying bedrock. Strata 7 has shallow (i.e. less than one meter) sandy soils while strata 4 have soils of mixed types (sand, clay, loam) which have depths greater than one meter.

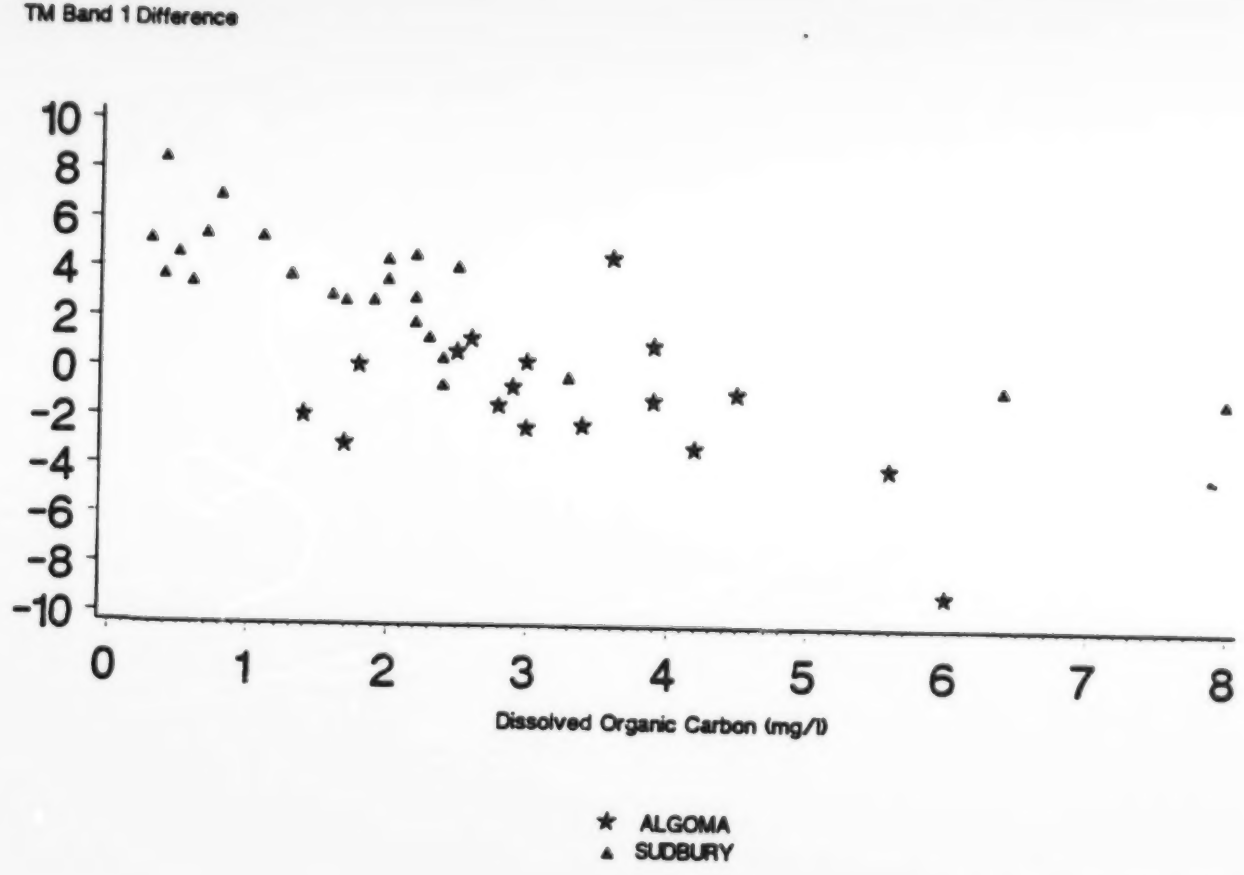

FIGURE 7. TM BAND 1 DIFFERENCES AND DISSOLVED ORGANIC CARBON FOR ALGOMA AND SUDBURY SITES, TM 1 (AUGUST 1986) - TM1 (MAY 1985)

Examination of the August-May difference values for TM band one produced similar results. Group A and group B strata were the same as above and the largest and smallest mean differences were found in strata 7 and 4 respectively.

The third type of analysis examines the relationship between values of the August-May difference from polygons which have similar ecophysical properties with the exception of sulfate deposition. For this case lakes were selected from units with sandy soils over granitic rock types and the sulfate deposition was 1.5 or 2.5 g/m2/yr. The TM band one DN values were found to be significantly different (at 5% level) based upon deposition level alone.

In addition to these seasonal analyses the spatial aspects of DOC reflectance sensitivity were investigated. Measured water quality parameters were used together with equation 2 to calculate a lake value of DOC sensitivity. The larger the derivative of reflectance with respect to DOC the more sensitive lake reflectance is to changes in DOC. The lake DOC sensitivity values were analyzed with the ecophysical strata and the mean sensitivity was determined for each strata as shown in Figure 8. These results indicate strata 5, 7, 8, and 9 will have lakes most sensitive to DOC changes. These strata also have the higher stratification sensitivity index values.

These preliminary analyses show that TM band one and seasonal difference DN values will differentiate sensitive from insensitive areas as well as like ecophysical strata with low and moderate deposition values.

4.0 TECHNICAL PROBLEMS

The CCT's for Path 19, Row 27 for May 12, 1987 and June 13, 1987 have been ordered but not received. These data are essential to completion of the technical requirements.

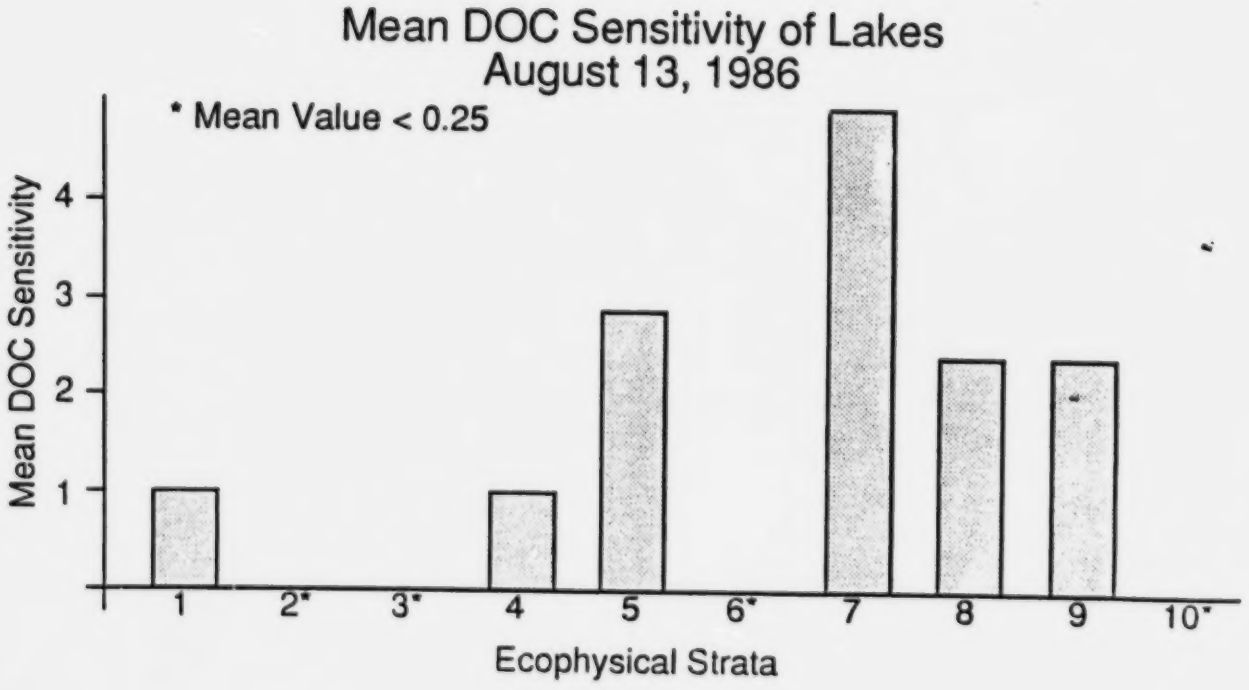

FIGURE 8

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5.0 PLANS FOR THE NEXT REPORTING PERIOD

All technical work on this contract will be completed by early November and a draft of the final technical report will be submitted by 1 December 1987. A request for an eight month no cost time extension will be made to allow time to submit final project results as a journal publication(s). In addition this request will allow us to report results as a participant in upcoming technical conferences.

6.0 REFERENCES

Bukata, R. P., J. E. Bruton, and J. H. Jerome, Application of Direct Measurement of Optical Parameters to the Estimation of Lake Water Quality Indicators. CCIW Scientific Series Report 140, 1985.

Effler, S. W., G. C. Schafran, and C. T. Driscoll, Partitioning Light Attenuation in an Acidic Lake, Canadian J. Fisheries and Aquatic Science, vol. 42, 1985.